Where is my hand?

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General discussion

Where is your hand? That is the question by which this thesis is inspired. More specifically, we designed a set of experiments to get more insight in proprioceptive position sense and the interaction between visual information of the position of the hand and proprioceptive information of this position. Although driven by the quest for fundamental knowledge on proprioception, the experiments were done with the concepts of tele-operation and haptic shared control in mind. In this section I summarize our findings on proprioceptive position sense and sensory matching, and discuss them with respect to implications for haptic devices.

Findings on proprioceptive position sense

This thesis started with three chapters investigating two basic factors that could influence proprioceptive position sense: external forces and skin stretch. In **chapter 2**, we exposed the hand to different horizontal force fields to examine whether external forces influence the proprioceptive position sense. In a sensory matching task subjects reached to visually presented positions with their unseen hand. In a vector reproduction task, subjects had to judge a distance and direction visually and reproduce the corresponding vector by moving the unseen hand. We found systematic idiosyncratic errors in the reaching for visual targets and in the haptic reproduction of visual vectors, but these errors did not vary systematically with the force fields. This suggests that humans are able to compensate for external forces in the horizontal plane applied to the hand both in localization and in reproduction of a direction and length.

An interesting additional finding in **chapter 2** is that all force fields induced an increase in the length of the trajectories of the movements, regardless of the direction of the forces. This might be due to the temporal difference between the efferent (leading the movement) and the afferent (lagging the movement) information of the position of the hand. For example, the force distorts the correct execution of the efferent motor plan, then after a small delay a correction can be planned based on the afferent feedback, another distortion occurs because the force fields are position-dependent, and after a small delay another correction is planned and so on. This suggests that although external forces do not influence the final position sense, they do affect proprioception during the movements.

In **chapter 3**, we investigated the effect of vertical force fields (and the torque differences due to these forces) on the proprioceptive position sense.

Because muscle torques counteracting gravity vary systematically during a movement of the arm, it has been suggested that torque differences that occur during a movement provide important information for judging the distance moved away from the body (e.g. Debats *et al.*, 2010). In two experiments, we tested constant vertical forces, resulting in a change in torque that was proportional to the gravitational torque, and gradient force fields, resulting in a dramatic change in the torque differences. No effects of the force fields on proprioceptive position sense were found, suggesting that external vertical forces on the hand do not influence proprioceptive position sense.

In **chapter 4**, we found that skin stretch manipulations systematically influence the proprioceptively perceived position of the hand. In an explorative study, we manipulated the skin stretch around the elbow by attaching elastic sports tape to one side of the arm. Subjects were asked to move the unseen manipulated arm to visually presented targets. We found that the tape induced a significant shift of the end-points of these hand movements. Although many questions were still open, we concluded from this study that skin stretch is an important factor in proprioceptive position sense.

Overall, the results of the first three chapters were not what we initially expected. We showed that force fields are not important for end-point control of proprioception, which was counterintuitive because it implies that humans would have an almost perfect measure of the exerted force to compensate for it. However, when changing perspective from scientific settings to situations in daily life, it might not be so surprising that (changes in) forces do not influence the perceived position of our hands. For example, pouring wine in a glass does not induce illusory movements towards the body for the hand holding the bottle and does also not induce illusory movements away from the body for the hand holding the glass.

Besides many enthusiastic reactions on our study on the effect of skin stretch on proprioceptive position sense, there were also a lot of comments. The people who had these comments can roughly be categorized in two groups: physiologists and motor control scientists. For the first group, the physiologists, our results are just a small extension of effects of skin stretch that they already knew and therefore they commented that the results might not be very new. The other group, the motor control scientists, seems to have some problems in accepting the outcome of the study. They argued that the results are probably not valid, because 1) skin stretch manipulation with the elastic sports tape would not be reproducible enough, 2) the manipulation would also influence muscle information (of which we know from the first chapters that it would not help), or 3) the amount of skin stretch could not easily be controlled. As described in **chapter 4** we did two studies with different subjects resulting in the same results for similar taping conditions on the inside of the arm, which I would say is quite reproducible. Furthermore, the fact that the amount of skin stretch might not be easily controlled might even strengthen our findings, because it shows that the effect does not arise only in specific conditions. Overall, I would like to argue that our results are especially interesting because of the different views from the scientific community. This shows that there is still a gap to bridge between research on human physiology and motor control.

Findings on sensory matching

The chapters in this thesis that describe studies on sensory matching and the consistency over tasks and across time (**chapter 5-7**) originate from a discussion during one of the weekly lab meetings. After talking about some data, the discussion focused on the question whether it is valid to refer to the same literature for studies with very different methodological characteristics. Of course the best way to answer these kinds of questions is to test them in an experiment. The first factor that we wanted to test is whether reaching with the index finger is similar to reaching with the fist, while holding the handle of haptic device in a power grip. The second question was whether reaching to targets that are presented on a board (2D) lead to similar matching errors as targets presented in free space (3D). In **chapter 5**, we tested these questions and found different visuo-haptic matching errors for the different experimental conditions, but no differences in precision and accuracy. Furthermore, the differences between the matching errors were not systematic across subjects, suggesting that the individual matching errors depend on the task characteristics, but that the overall precision and accuracy do not.

In chapter 5 we started to develop a method to quantify the consistency between the matching errors in different experimental conditions. While fine-tuning the method we realized that it would be interesting to know how consistent sensory matching errors are in the same task over a longer period of time. Are visuo-haptic and haptic-haptic matching errors consistent over time? In **chapter 6**, we showed that the systematic matching errors were consistent across time intervals of at least a month. Within this time period, individual subjects' matches were as consistent as one could expect on the basis of the variability in the individual subjects' performance within each session. Thus individual subjects make idiosyncratic errors, which are, in similar circumstances, consistent across long periods of time.

Despite the nice results on quantifying and describing the consistency of sensory matching errors, it is still puzzling where these errors originate. In **chapter 7** we presented the results of two experiments in which we investigated the relevance of posture, hand and task on the sensory matching errors. In the first experiment, we examined the consistency between visuo-haptic matching errors for the two hands and for different postures (hand above or below a board). We found that the matching errors depend on the posture and differ between the hands.

In the second experiment, we designed sets of tasks that involved the same matching configurations. For example, we compared matching errors when moving with the unseen index finger to a visual dot, with matching errors when moving a visual dot to the unseen index finger. We found that the matching errors are not invertible, so moving a visual dot towards the unseen index finger is not the same as moving the unseen index finger to a visual dot. Furthermore, moving both index fingers to the same visual dot resulted in a different mismatch between the hands than directly matching the two index fingers. Additional analyses showed that the results could not be due to the difference in the active or passive proprioceptive position sense or proprioceptive drift. Therefore we could conclude that sensory matching is not simply based on summing sensory biases. Transformations seem to play an important role, and these transformations seem to depend on the movements that need to be made. This suggests that the brain takes both the end-point control and the motor action that is required to reach the desired position into account when transforming the information between the senses and creating the motor plan. Considering this it is even more surprising that humans make the same visuo-haptic matching errors in the same task when returning to the same task weeks later (**chapter 6**). Further research and perhaps some good modeling should help us to understand the basics of sensory matching better.

Implications for tele-operation and haptic shared control

"Could you tell me how the human haptic system works? Then I can implement the relevant parameters into the design of my new haptic devices." This was more or less the first question that I got when joining in the H-Haptics kick-off meeting in 2011. I was a bit shocked; how could someone expect to describe human sensory systems by a few simple parameters? Now, some years later, we understand each other much better and within the project we had very nice and fruitful collaborations (e.g. Kuiper *et al.*, 2015). Although I would have wanted to, I still cannot tell how the human haptic system completely works, because unfortunately, scientific research leads more often to more questions than to clear answers. However, in the experiments described in this thesis we found interesting and useful aspects with respect to the design of haptic devices. I will summarize these findings and the recommendations following from them in this section.

First, we found that external forces on the hand do not influence the perceived position of this hand (**chapter 2** and **3**). These results can be translated to the design of haptic guidance forces and the regulation of forces in haptic systems. Our results support the conceptual idea in haptic shared control that forces can be used to give information to the human operator. These forces do not interfere with the proprioceptive position sense and therefore forces can be used as an independent information channel. Furthermore, our findings in **chapter 3** show that vertical forces and torques do not influence the perceived position of the hand, which suggests that gravity compensation can be used without changing the perceived position of the hand.

From our study on skin stretch (**chapter 4**) we can learn that we have to be careful in attaching exoskeletons (e.g. Perry *et al.*, 2007), prostheses (e.g. Akhtar *et al.*, 2014) or other wearable haptic devices (e.g. Bouzit *et al.*, 2002; Minamizawa *et al.*, 2007) to the skin. Attaching them haphazard to the skin might induce unwanted unnatural skin stretch patterns, which could lead to errors in the perceived position of the hand or perhaps even illusory movements.

Since humans have very consistent sensory matching errors (**chapter 6**) it was an interesting thought to see whether using these matching errors to optimize haptic shared control by individualizing guidance would work. In **chapter 8** we presented the proof-of-principle that the concept of individualizing guidance leads to better performance than veridical guidance. We aligned the haptic guidance with the position of the visuo-haptic matching error. One could argue that, by doing this, the subject does not end at the correct (visually presented) position. However, we would argue that in tele-operation systems the position and movement of the user, the master and the slave are related but most of the times not identical (e.g. Niemeyer *et al.*, 2008; Pierce & Kuchenbecker, 2012) and therefore, it does not matter whether you correct the movement or position on the side of the user or at the side of the slave and environment. Besides this theoretical argument, we also tested it in an experiment (Van Beek *et al.*, 2016). In this study, the visual information was shifted with respect to the haptic guidance to overcome individual visuo-haptic matching errors, while maintaining the desired reaching position spatially constant. Again, performance increased (higher precision and accuracy) when the individual sensory matching errors were taken into account compared to the veridical situation (Van Beek *et al.*, 2016).

In **chapter 5** we showed that the precision of a reaching task does not depend on the end effector, implying that the interface can be designed based on other parameters and does not have to take a specific grip into account. However, the grip and the posture of the operator might influence the systematic error in the execution of the task (**chapter 5** and **7**), which makes it important that user settings based on individual sensory matching should be created in the same set-up that is used as the real interface.

Chapter 9 is a bit the odd one out in thesis since it is the only chapter looking at temporal aspects of haptic perception. However, the results are certainly worth mentioning with respect to the design of haptic systems. In an admittance-controlled haptic device, input forces are used to calculate the movement of the device. Although developers try to minimize delays, there will always be delays between the applied force and the corresponding movement in such systems, which might affect what the user of the device perceives. In this experiment we found that these delays in haptic human-robot interaction influence the perception of mass. For the design of haptic systems it is therefore very important to realize that technical aspects, like delays, can be perceived and/or interpreted as object characteristics.

To keep in mind for the design of haptic systems

In general:

- Torques (and gravitational compensation) do not influence proprioceptive position sense (chapter 3)
- Reaching with the handle of a haptic device in a power grip is as precise as reaching with the index finger (chapter 5)
- Delays can influence perception (chapter 9)

Haptic shared control:

- Forces do not influence reached end points, but they can influence the paths taken to reach this end points (chapter 2)
- Individualizing haptic guidance based on sensory matching improves performance (chapter 8)
- Individual settings for haptic guidance can be kept similar for long periods of time, because the sensory matching errors are consistent (chapter 6)

Wearable haptics:

- The human proprioceptive system cannot compensate for unnatural skin stretch, which could induce side effects in wearable haptics (chapter 4)